LOW SALINITY FLOODING: EXPERIMENTAL EVALUATION AND NUMERICAL INTERPRETATION

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1. ABSTRACT

Low Salinity Flooding (LSF) is an emerging technology to improve oil recovery for both sandstone and carbonate reservoirs. Extensive laboratory experiments investigating the effect of LSF are available in the literature. To quantify the low salinity effect, spontaneous imbibition and/or tertiary waterflooding experiments have been reported. In only a few published cases, the experimental data was interpreted using numerical simulation to derive relative permeability curves for both low and high salinity water, to be used in field simulation. A critical review of the literature data shows a wide spread in the LSF response in both pressure and recovery. Moreover, most of the flooding experiments reported in the literature are performed at a low flow rate, of ~1 ft/day, which may lead to a significant capillary end effect and, consequently, to a possible overestimation of the LSF effect.

The focus of this paper is on: 1- The experimental procedures used for proper evaluation of the LSF effect; 2- Reporting experimental data performed on sandstone samples in both tertiary and secondary mode waterflood; 3-The numerical interpretation of the laboratory data to obtain relative permeability and capillary pressure curves for both high salinity (HS) and low salinity (LS) water, to be used in reservoir simulation to quantify the benefit of LSF on reservoir scale and 4- Investigating whether the tertiary flooding experiments can be used to derive relative permeability curves for both HS and LS waterflooding.

The main conclusions of the study are: 1- The LSF effect measured during low rate flooding experiments (i.e., field rate) is not representative for the field scale as it is usually dominated by capillary end effect. Therefore, the low rate (raw) coreflood data will suggest a larger LSF benefit than would actually be the case; 2- The tertiary mode experiments cannot be used to derive the LS relative permeability curves as it only spans a narrow saturation range during LSF and 3- Both tertiary and secondary mode corefloods performed using multi-rates are required to obtain relative permeability curves for HS and LS water.

2. INTRODUCTION

Low salinity waterflooding (LSF) is an emerging technology in which the salinity of the injected water is optimized to improve oil recovery over conventional waterflooding. Over the last two decades several groups have published laboratory and field data which show extra oil recovery upon injection of LS water. However, a wide range of responses in the extra oil recovery is reported in the literature, from 0 to more than 20%. To extrapolate laboratory results to the field scale and to separate several potential underlying LSF mechanisms, measuring and accounting for the pressure drop over the core during flooding experiments is essential. In a number of cases reported in the literature no pressure data was shown. In the cases when the pressure data was available, a wide range of pressure responses is observed. In some cases a pressure increase is observed once low salinity is injected. The effect of such pressure increases on laboratory results is rarely discussed.

While the debate on the microscopic mechanism of LSF is still ongoing, it is widely accepted that wettability alteration from non-water-wet towards more water-wet is responsible for the improvement in oil recovery. Wettability alteration leads to two effects that can improve oil recovery. Firstly, it changes the relative permeability curves towards lower water relative permeability and higher oil relative permeability at a given water saturation. Secondly, it may also reduce residual oil saturation upon injection of low salinity water. This paper will focus on two main issues: 1- The experimental procedures to evaluate the potential of LSF in the laboratory, and 2- The numerical interpretation of the laboratory data to obtain relative permeability and Pc curves for both HS and LS water to be used in reservoir simulation in order to quantify the benefit of LSF on reservoir scale.

3. EXPERIMENTAL PROCEDURES TO QUANTIFY LSF

In this section, the laboratory experimental protocols for LSF are discussed. The objectives of the experimental protocols are to:

- Assess the potential of increased oil recovery by LSF in the laboratory
- Determine the relative permeability and Pc curves for HS and LS brine to enable upscaling the LSF benefit to reservoir scale
- Assess the potential formation damage by LSF due to clay swelling. This is done by performing brine compatibility tests. However, it is important to note that this experiment should be done in the presence of oil, experiments performed at 100% brine saturated samples are not representative.

A critical review of the data reported in literature shows that:

1- Most of the flooding experiments (apart from few exceptions, see [1-2]) were performed using low flooding rate (~ 1 ft/day). Under these conditions, capillary forces may dominate the flow and oil production will be strongly affected by capillary end effect, especially for non-water-wet rock, see [3]. As LS water is injected, and if the wettability is altered to a more water-wet state, the capillary end effect will be reduced leading to an increase in oil production.

2- In a few cases presented in the literature, a lower IFT between LS water and crude oil was reported. For example, Gupta *et al.* [4] reported a factor of 2 reduction in IFT when phosphate was added to the injected brine. A reduction of the capillary pressure by a factor of 2 is then expected which leads to a lower capillary end effect and an increase in oil production for the non-water-wet samples.

3- Several papers also reported significant increase in the viscous pressure drop upon injection of LS water, see [5-10]. Likewise, this increase in viscous pressure leads to a reduction in capillary end effect and an increase in oil recovery at the core scale.

A combination of one or more of the observations mentioned above (i.e., low rate experiments, lower IFT and higher viscous pressure) can explain at least part of the extra recovered oil during LSF. This is especially important for experiments run on short core samples and/or high permeability as the capillary end effect for such samples has a relatively larger impact on oil recovery [3]. This shows that part of the effect claimed in literature may be attributed to experimental artefacts and may not be observed on reservoir scale where no capillary end effect is experienced. Therefore, the raw coreflood data obtained using low rate tests may suggest a larger benefit than would actually be the case.

To minimize any experimental artefacts, flooding experiments should be designed to overcome the capillary end effect by either using high rates and/or using long core samples. Numerical simulation of the raw experimental data will also help to correct the results for the capillary end effect. Full use of in-situ saturation data, if available, as part of the history matching process is an essential quality checking step. Monitoring of in-situ water saturation profiles at least during the stationary part of the various flooding stages is strongly recommended because it:

1- Improves the uniqueness of the history match.
2- Provides direct evidence of the LSF effect, i.e. it shows whether the additionally swept oil is produced uniformly along the core and hence representative for field scale or only from the region close to the outlet, not relevant to field scale.

In this study we have used all means to overcome capillary end effects, i.e., some of the experiments were run using long core samples up to 20 cm, higher injection rates were used during the HS waterflood to overcome capillary end effects before injecting LS water and all core flooding data were interpreted using numerical simulation.

The other part of the LSF program often used in the industry is to run spontaneous imbibitions (SI) experiments. Such experiments provide a direct evidence of the change of wettability upon using LS water. However, in our experience, no correlation was found between SI data and the extra oil recovery during tertiary flooding experiments. This paper will focus mainly on the flooding experiments.

4. SIMULATION MODEL

The model used to interpret the LSF experiments is based on the same principles as those used for chemical flooding and it is similar to the one discussed in [11] but with important differences as shown below. The numerical interpretation was performed using the Shell in-house reservoir simulator MoReS. The LSF simulation model consists of the following:

1- The salinity dependency of relative permeability, capillary pressure and water viscosity is modeled by means of passive tracers.

2- A passive tracer is assigned to the water phase to track the change of salinity as water is injected and it mixes with the formation water. The model has the functionality to assign a different level of diffusion and dispersion for injected water than for the water phase.
3- The resulting grid block salinity is used to interpolate, at each time step, between the viscosity of the HS and LS water.
4- The relative permeability and Pc of each grid block are function of salinity:
   a. The relative permeability and Pc curves for HS and LS water are inputs, see Figure 1. The HS curves are used for any salinity higher than a cut-off value defined by the user (HS-cut-off) and the LS curves are used once the salinity in the grid block reaches any salinity lower than cut-off value (LS-cut-off).
   b. The relative permeability and Pc curves are then interpolated between the HS and LS curves for any salinity between the two cut-off values.
   c. The residual oil saturation is also a function of salinity which is interpolated between the two HS and LS S_{orw} values.
5- The relative permeability curves (HS and LS) start from the same connate water and have the same oil end point at S_{wc} (i.e., the same $K_{row}(S_{wc})$). The reason is that the connate water was established in the presence of HS and the oil end point is measured in the presence of HS water irrespective of the type of injected water.
6- The above model assumes almost an instantaneous LS effect caused by the assumption of "full mixing" between the LS and HS water and instantaneous wettability alteration. In some tertiary mode experiments a delay in the oil production is observed upon injection of LS water. In these cases, where the assumption of fully mixing doesn't hold, the delay in the LS effect is modeled by linearly interpolating between the HS and LS relative permeability curves assuming the effect is not only a function of salinity but also of time. Therefore, the relative permeability starts to change once the HS-cut-off value is reached and the change takes a certain period of time even if the salinity reaches the LS-cut-off value. An example is shown in section 7.

5. LSF EXPERIMENTS: LABORATORY RESULTS AND NUMERICAL SIMULATION

Reviewing the literature shows that numerical interpretation of the laboratory data is rarely done. This section focuses on numerical simulation of LSF experiments, both in tertiary and secondary mode. The objective is to investigate what we can get out of the flooding raw data and how much of the measured effect is real. The following questions will be discussed: 1- Is the LSF effect seen in the low rate experiments relevant to field scale or is it (at least) partly an experimental artefact? 2- Can tertiary mode experiments be used to measure the LS relative permeability curves? 3- If not, how can LSF relative permeability curves be obtained reliably?

5.1 Numerical Simulation of Low Rate Tertiary Mode Experiments

Figure 2a shows an example of a low rate tertiary mode coreflood experiment where HS water was injected followed by LS water, at an injection rate of 0.05 cc/minute for both the HS and LS brine, which is equivalent to 1 ft/d. At first sight the data seem to indicate more than 7% extra oil recovery due to LSF. Just like in this example, in most of the tertiary LSF experiments reported in the literature, the oil recovery as a function of PV or time is the only available data. Figure 2a shows also a history match of the production data using the relative permeability and Pc curves shown in Figs. 2b and 2c. To quantify how much of the extra oil production during LSF could be due to capillary end effect, three more simulation runs were performed (see Figure 2d). The first simulation run was performed with the HS relative permeability curves and both HS and LS Pc curves (Change in Pc only), the second run was performed with the HS Pc curve and both HS and LS relative permeability curves (Change in kr only) and the third run was performed with HS curves (no change in Pc or kr), see Figure 2d. The results demonstrate that in this case the change in the Pc curve has more effect than the change in the relative permeability curve. Therefore, the extra oil recovery during the LSF in this experiment cannot be fully attributed to a real LSF effect as part of it is clearly due to reducing capillary end effect, caused by making the shift in the Pc curve becoming less oil-wet.

Furthermore, we will examine now the uniqueness of the history match presented in Figure 2a in order to answer the question whether this kind of tests can be used to obtain the relative permeability curves of both HS and LS water. Figure 3 shows four different sets of relative permeability curves used to obtain the same match shown in Figure 2a. The Pc curves used in combination with the relative permeability curves are not shown. Significant differences are evident between the relative permeability curves especially in the low water saturation range. This shows that for this case the history match is not unique and cannot be used to obtain the relative permeability curves of HS and LS water. The saturation range where the history match is sensitive to the relative permeability curves is limited to about 10 saturation units for the HS flooding (saturation between breakthrough and end of the HS flooding) and less than that for the LSF. Moreover, the absence of Pc and pressure data makes it even more difficult to obtain meaningful relative permeability curves over the narrow saturation range after breakthrough.

5.2 Comparison of the Low Salinity Effect in Low Rate and High Rate Experiments

Figure 4 shows the results of two tertiary mode experiments, where both water saturation and pressure drop are plotted as a function of time. The two samples have been initialized using HS formation water (260,000 ppm) at S_{wi} of 0.32 and 0.42, respectively. After aging both samples for four weeks to restore wettability, the first sample was flooded with HS water using a rate of 0.05 cc/minute. Then the sample was flooded with LS water (1,500 ppm TDS) using the following rates: 0.05, 0.5 and 2 cc/minute. The second experiment was flooded first with HS water using the following rates: 0.05, 0.5 and 2 cc/minute and then switched to LS water at a rate of 2 cc/minute. The objective of running these experiments is to compare the LSF effect if LS is injected after low rate or high rate HS flood.

The samples have porosity of 0.22 and 0.265 and permeability of 58 and 89 md, respectively. As shown in Figure 4, the pressure drop decreases when switching from HS formation water to LS water. This reduction in pressure drop is a result of three factors: 1- The viscosity of the LS water is lower than that of the formation water (0.43 cP compared to 0.72 cP); 2- Due to wettability alteration upon injection of LS water, the capillary pressure becomes either less oil-wet or even water-wet (see Figure 1), which reduces the capillary pressure and subsequently the overall pressure drop and 3- In the case of extra oil production during LSF, the water relative permeability will increase which also decreases the pressure drop. However, the water permeability end point may decrease due to wettability alteration which leads to higher pressure drop. In our experiments, we very rarely observe any pressure increase, which shows that the factors contributing to reducing pressure drop are more important and that no formation damage occurs.

The data of the low rate tertiary experiment shows low oil recovery (50% of OIIP) during the formation water flooding and an extra oil recovery of about 7% upon switching to LSF. It is important to note that the oil saturation at the end of the experiment is far from S_{orw}. Therefore, the extra oil recovered during LSF cannot be assigned to a reduction in $S_{orw,}$ but rather to a change in relative permeability and/or Pc curves of the sample. The fact that the sample was not at S_{orw} is demonstrated by increasing the LSF rate which resulted in significant amount of extra oil recovery. The extra oil produced (> 15%) during high LSF rates is not due to oil stripping or capillary de-saturation as the capillary number even at the high rates is still very low, around 10^{-6}. This shows that in tertiary mode experiments a more accurate quantification of the LSF effect is achieved if the sample is first brought to S_{orw} during formation water flooding before starting the LSF.

The high rate tertiary mode experiment (Figure 4b) shows also significant increase in oil production as the injection rates increases, which clearly demonstrates that the oil saturation at the end of the low rate is far from S_{orw} as the production is dominated by capillary end effect. After increasing the flooding rate so that the pressure drop is high enough to overcome capillary forces, LSF started using the last rate of the formation waterflooding, i.e., 2 cc/minute. Only 2-3% of extra oil is produced and the pressure drop was reduced. This extra oil production is a true reduction in S_{orw} but it is significantly less than the extra oil recovery during the low rate experiment (2% compared to 7%). The residual oil saturation at the end of both experiments was quite similar, about 15%.

To conclude the above discussion, the low rate LSF experiments alone are not adequate to quantify the potential benefit of LSF. Better experimental design is required to obtain the relative permeability curves, as discussed in the subsequent sections.

6. HOW CAN REPRESENTATIVE LSF RELATIVE PERMEABILITY CURVES BE OBTAINED?

A combination of tertiary and secondary mode experiments are required to obtain relative permeability curves of both HS and LS water. Figure 5 shows two experiments, one tertiary and one secondary mode flooding experiment. Both experiments are run as multi-rate Unsteady State tests in order to minimize the capillary end effect, improve the uniqueness of the history match of the raw data and ensure the samples reach S_{orw}. The flooding procedure is similar to the high rate tertiary mode experiment described in the previous section. In the tertiary flooding experiment the rates are 0.05, 0.5, 2 and 5 cc/minute for both HSF and LSF. The same rates are used in the secondary LSF experiments. As shown in the figure, the samples did not reach S_{orw} during the first low rate and significant volumes of oil were produced at higher rates. The S_{orw} reduction after switching to LS in the tertiary mode experiment is only 2-3%, similar to the experiment shown in Figure 4b.

Figure 5 also shows the history match of the raw data to derive relative permeability curves. The samples did not start from connate water, which means the water relative permeability at initial water saturation is not zero and the oil relative permeability at S_{wi} is lower than K_{row} (S_{wc}). In order to reflect the mobility of the oil and water at the start of the flooding experiments the relative permeability curves used in the history matching were extended to lower water saturation (25%). The relative permeability and Pc curves used to history match both the oil production and pressure data are shown in Figure 6. The figure shows the HS Pc and relative permeability curves extracted from the tertiary mode experiment and the LS Pc and relative permeability curves extracted from the secondary mode experiment. The relative permeability curves shown in Figure 6a are more accurate for water saturation higher than the breakthrough saturation. While the tertiary mode experiment alone cannot be used to derive the LS relative permeability curve, combining the two experiments gives more confidence in the two relative permeability curves.

The Pc curves cannot be derived from the flooding data with the same confidence. In this case no capillary pressures were measured. However, the pressure drop of the multi-rate experiments is an important data that constrains the Pc curve. Moreover, we did have a number of spontaneous imbibitions (SI) experiments on samples from the same reservoir. These SI experiments showed either no or only few percentage of oil produced when the imbibing fluid was HS water. Switching the imbibing fluid from HS to LS water, produced about 10% extra oil. Therefore, the imbibition Pc curve for the HS is expected to be mainly forced imbibition while for LS it will switch to negative values at slightly higher water saturation but it is still mainly negative, i.e. a forced imbibition Pc curve. Therefore, the Pc curves used in history matching the LSF data were guided by the above constraints, i.e., proper match of pressure data and reflecting the maximum SI that can potentially take place. The Pc curves shown in Figure 6b are both negative (forced imbibition), which may not be representative. Therefore, the data in Figure 5b was history matched using different combinations of relative permeability and Pc curves, where different levels of SI was assumed guided by the SI data. Then the relative permeability curves were adjusted to get the same history match. The different combinations of LS relative permeability and Pc curves used to obtain the same match are shown in Figure 7. As shown in the figure the change in relative permeability is insignificant. Therefore, the relative permeability curves can be derived with more confidence from these experiments while a range of possible combinations of Pc curves can be defined. To measure the Pc curves more accurately, dedicated experiments are required which will also improve the uniqueness of the history match of the flooding experiments. As also discussed in section 3, monitoring the in-situ saturation profiles will also improve the uniqueness of the history match.

7. COMPARING TERTIARY AND SECONDARY MODE EXPERIMENTS WITH CLEAR LSF RESPONSE

In this section, an example of tertiary and secondary mode experiments is presented using long core and high rates which show a clear response in both reduction in S_{orw} and clear wettability alteration. The experimental program consisted of 3 experiments:

1- Tertiary spontaneous imbibition experiment to check the initial wettability state of the sample and the potential change in wettability by low salinity. The sample was initialized to S_{wi}=32% and the experiment was performed on a single plug.
2- Tertiary mode LSF experiment following the same procedures describe above where rates for both HSF and LSF were 0.03, 0.15 and 1 cc/minute which are equivalent to 1, 5 and 33 ft/day. The experiment was performed using a composite core of 16 cm long, initialized at S_{wi}=0.34.
3- Secondary mode LSF experiment using the same rates as above, i.e., 0.03, 0.15 and 1 cc/minute. The experiment was performed using a composite core of 20 cm long initialized at S_{wi}=0.30.

The salinities of the HS and LS water were 17,000 ppm and 1,500 ppm, respectively. Figure 8 shows the experimental data of the three experiments. As shown in Figure 8a, the high salinity water spontaneously imbibed up to S_w=0.66 and after switching to LS water the water saturation increased to 0.69. The tertiary mode LSF experimental data are shown in Fig 8b. The figure shows:

1- During both HSF and LSF, oil was produced only during the first low rate of 0.03 cc/minute. Increasing the rate to 0.15 and 1 cc/minute did not produce any extra oil.
2- This experiment shows that in the case of the absence of a capillary end effect, increasing the rate does not strip any extra oil as long as the rate does not exceed the critical capillary number. The absence of the capillary end effect is due to using long core and the relatively water-wetness of the samples.
3- During LSF, oil production started after injecting 3 PV of water. This could be due to mixing with high salinity water or the time it needs for wettability alteration.

The secondary mode experimental data is shown in Figure 8c. The production data shows that there is hardly any extra production after breakthrough, which is an indication of strongly water-wet sample. Moreover, the pressure is higher than that of the tertiary mode experiment though the permeability is comparable, about 20 mD. This high pressure is another indication of more water-wetness compared to the tertiary mode experiment. The residual oil saturation at the end of the experiment was 22%. Increasing the rate up to 5 cc/minute which is equivalent to 165 ft/d did not lead to any extra oil recovery. Both flooding experimental data were history matched as shown in Figure 8. However, since the samples were relatively water-wet, the saturation at breakthrough was high especially for the secondary mode experiment. Therefore, the history match was mainly sensitive to the water relative permeability end points which are 0.05 and 0.006 for the tertiary and secondary mode experiments, respectively. The tertiary flooding experiments can be used to extract part of the relative permeability curves, especially that the oil end point was measured directly at connate water. The relative permeability curves used to history match both oil production and pressure drop are shown in Figure 8d. As discussed in section 4, the delay in the oil production during the LSF cannot be matched using the full mixing model. To history match the data shown in Figure 8b, we used 25 hours for the relative permeability of a grid block to linearly interpolate between the HS and LS relative permeability curves. This value is a matching parameter and it depends on the HS-cut-off and LS-cut-off values used in the model which are not very well defined.

8. CONCLUSIONS

This paper focused on the experimental procedures and numerical simulation of LSF and discussed issues that could potentially have affected some of the LSF results reported in the literature. The main conclusions of this paper are:

1- Low salinity waterflooding data reported in the literature performed at field rates may have suffered from capillary end effects which sheds some doubts on field relevance of the additional recovery values reported in such experiments.

2- The low rate coreflood experiments are not sufficient to properly quantify the potential benefit of LSF, additional experiments and preferably in-situ saturation monitoring is needed. This is because:
   a. The low rate experiments cannot be used to quantify the reduction in S_{orw} due to the impact of capillary end effect and
   b. The relative permeability curves cannot be accurately derived because the history match of the production data of such experiments is not unique.

3- Using high rates during the HS salinity flooding experiments does not lead to stripping S_{orw} as long as the capillary number is below the critical capillary number.

4- No formation damage was observed in this study during LSF experiments performed in the presence of oil. In most experiments we observed a decrease in pressure drop once LSF started due to lower viscosity and reduced capillary pressure.

5- To obtain representative relative permeability curves to be used in reservoir simulation a combination of tertiary and secondary mode experiments is required.

6- A simulation model based on the passive tracer approach is presented and used to interpret laboratory LSF data to derive both HS and LS relative permeability and capillary pressure curves.

7- Numerical simulation is a very useful tool in interpreting the LSF experiments and it helps to unravel the capillary end effect from real LS effect.

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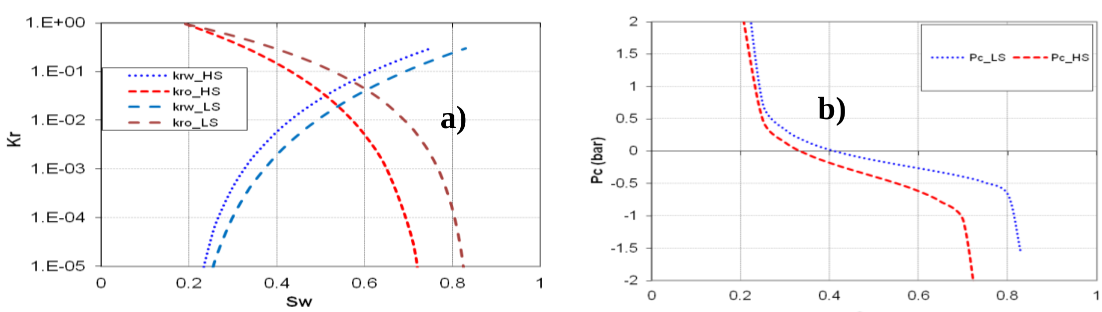

Figure 1: Typical relative permeability (a) and Pc curves (b) used for the interpretation of LSF experiments

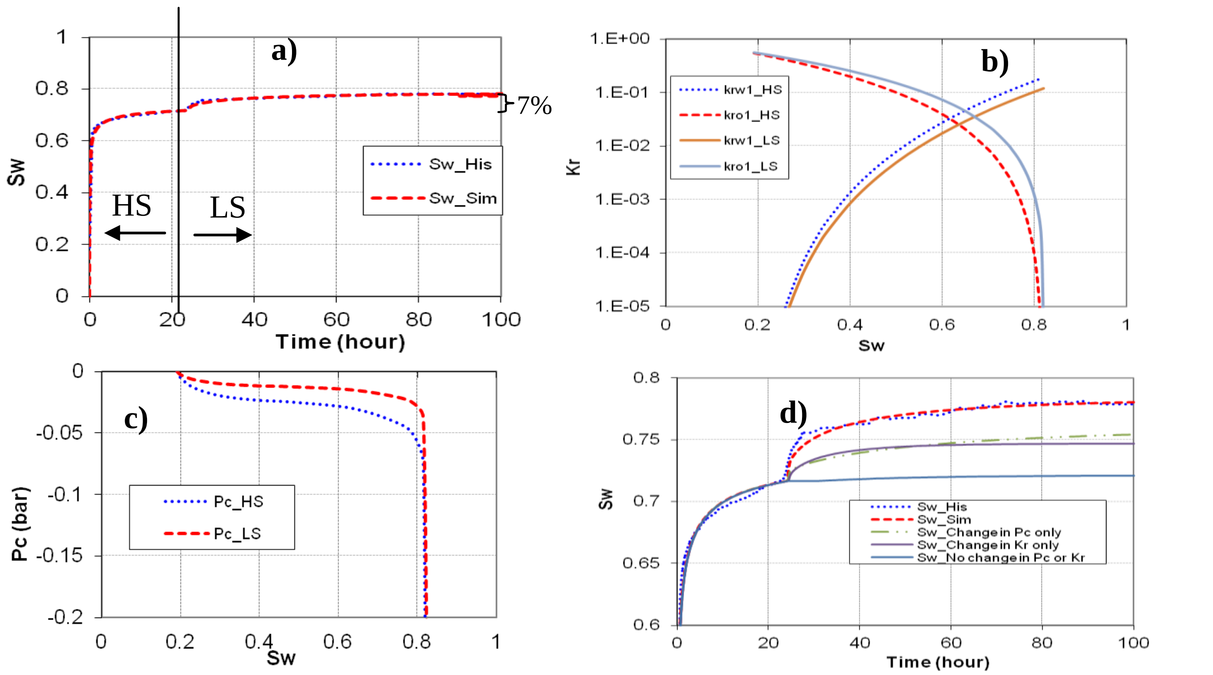

Figure 2: An example of a low rate tertiary mode LSF core flood a) Production data and history match, b) Relative Permeability curves, c) Pc curves and d) Simulation results which demonstrates that the change in Pc curves has more effect on oil production than the change in relative permeability curves.

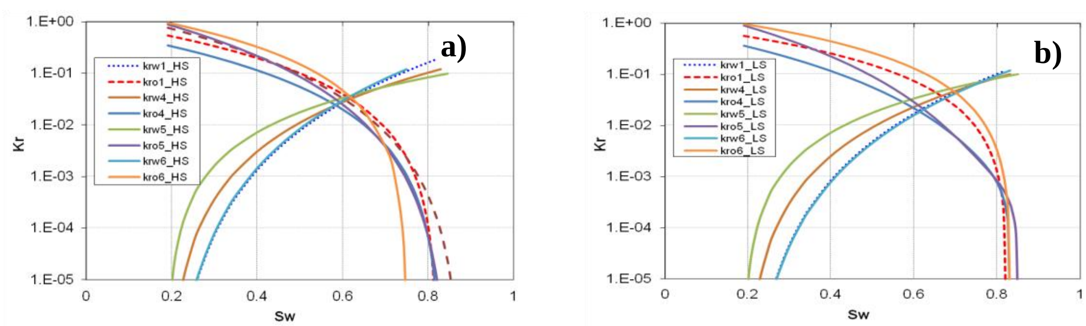

Figure 3: Different sets of HS (a) and LS (b) relative permeability curves that can be used to history match the data shown in Figure 2a, as the match cannot be properly constrained.

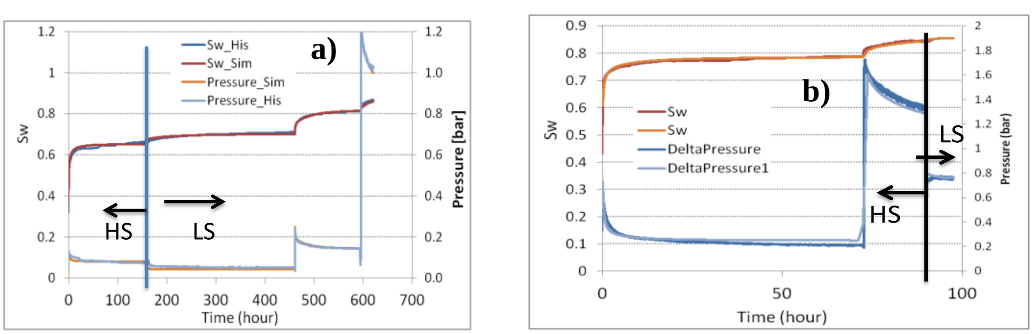

Figure 4: Water saturation and pressure drop data for two tertiary mode LSF core floods, wherein the switch to LS brine is conducted at either low rate (a) or high rate (b). Rates are given in the main text.

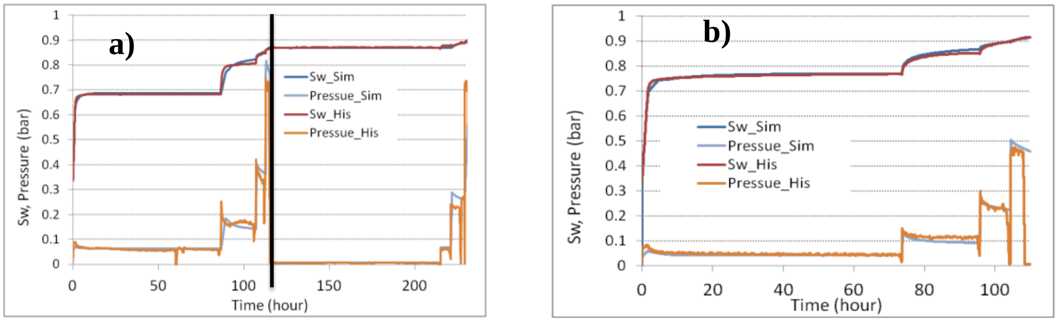

Figure 5: a) Tertiary and b) secondary LSF core floods with the history-matched data

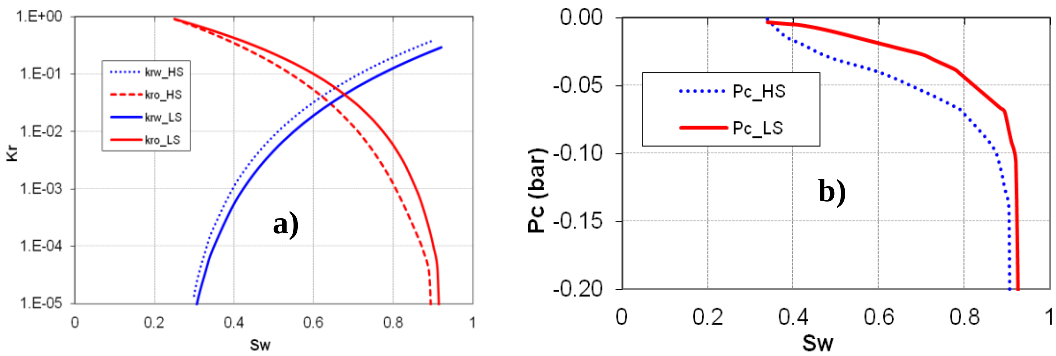

Figure 6: a) HS and LS relative permeability curves and b) Pc curves used to history match the data shown in Figure 5. The HS curves are more constrained in tertiary experiment while the LS curves are more constrained in the secondary mode experiment.

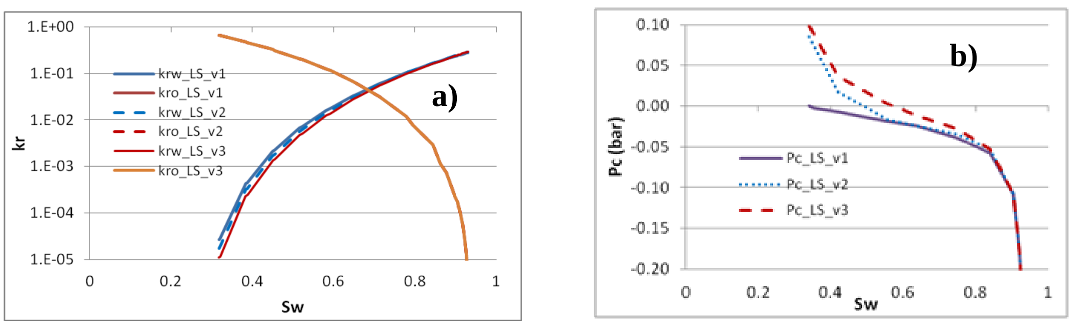

Figure 7: a) HS and LS relative permeability curves and b) Pc curves that history match the data shown in Figure 5.

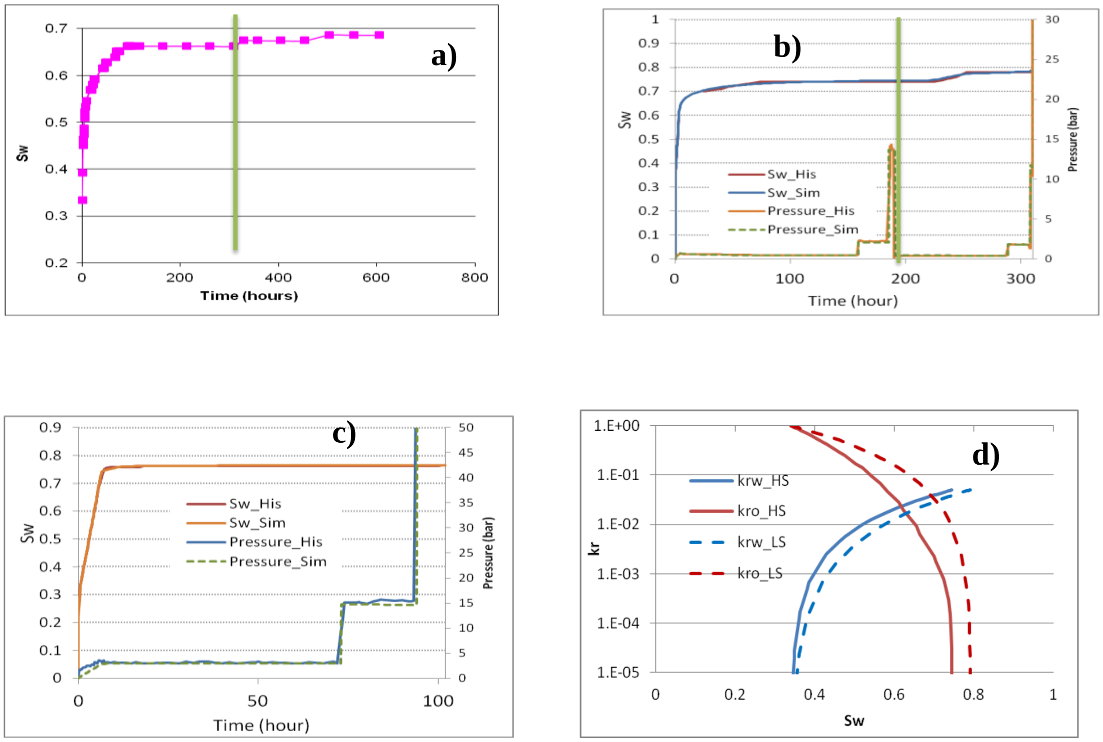

Figure 8: LSF data example a) Spontaneous imbibitions, b) tertiary USS data and history match, c) Secondary mode experiment showing similar S_{orw} as the tertiary mode experiment, and d) The HS and LS relative permeability curves used for the history match shown in 8b.